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Working Memory, Age, Crew Downsizing, System Design and Training

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Working memory is a central component of many models of cognitive function and workload (c.f. Baddeley and Gathercole, 1993). The ability to store information on a short-term basis for rapid retrieval or to retain cues to aid recall of long-term information is often presented as a major bottleneck in human performance. Some models of human information processing (Pashler, 1998) place the bottleneck in the central processing phase between input and output and relate it to sequential processing, response selection or limited capacity processing, via a central executive. Many models of attention place the bottleneck between early in stimulus processing (Broadbent, 1957) or at both early and late stimulus procesing (Norman, 1968).

Wherever the bottleneck exists, or if its position varies with processing experience or attentional states, there has been a general consensus that the central processing phase is of limited capacity (Broadbent, 1958), from the very earliest work. This short term processing and storage capacity will be called working memory as termed by Baddeley and Hitch (1974). Working memory deals with memory processes and storage held in a quickly accessible store in preparation for processing or during the processing of information, where the store has limited or finite capacity[i]. Analyses of accidents in safety critical systems suggest that memory lapses are an important source of errors and serve to create fertile conditions for accident development (Redmill and Rajan, 1997).

It is likely that working memory holds the information to be processed, the results of processing and the operators used to process the information. Thus, capacity can be exhausted by complex operators, large bodies of information to be processed or multiple results following from operations. This can be contextualized in air-warfare in the following examples. An operator examining the Radar Warning Receiver (RWR) can see multiple traces from different headings and the frequencies on different headings may mean different things, this represents complexity in the data. The tracks on an RWR must sorted into friendly and potentially hostile forces, and in some cases coalition forces may be flying aircraft equivalent to those flown by hostile forces. The latter case, where friendly forces operate aircraft equivalent to hostile forces, represents a case where the operators and tests applied to sort tracks are more complicated and it may require data fusion by the man or machine to unequivocally identify tracks as friendly or hostile. The same complexity of sorting can generate multiple results where there are failures to unequivocally identify tracks because multiple solutions must be considered. Even where single tracks are shown on the RWR the separation of tracks may be such that multiple sources, multiple aircraft, appear to be single tracks.

Thus, even a simple sorting analysis has uncertainties and multiple interpretations may be required to prime the operator for alternative responses. Where alternatives are not brought to mind and place-marked for future reference the situational awareness of the operator is by definition weaker (Endsley, 1995a, 1995b, 1988). The significance of situational awareness in air-warfare can easily be appreciated by consideration of commentators and writers in the area of combat (Spick, 1999; Handleman, 1999; Rendall, 1997; Press, 1999). While the reduction in the number of alternatives considered by older experts, through judicious selection is possible, there are still likely to be difficulties in retaining place-markers in memory for the different alternatives, which has been accepted in reviews of ageing performance (Proctor and Dutta, 1995), such that memory performance

[i] *More recent analyses based on skilled memory (Ericsson and Delaney, 1999) consider the possibility that the limits are not as great as those observed in more abstract tasks within the laboratory. However, it remains a matter for conjecture how these limits are overcome by either functional or structural routes, which in turn leaves open to question what limits memory imposes on expert performance.*

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is still a key issue. There are kind interpretations of the older individual suggesting that more experienced operators are more selective so they simply consider the most likely alternatives. Such an interpretation suggests that older and more experienced operators would by definition be subject to the confirmation bias as a consequence (Huey and Wickens, 1993).

It is clear that any changes in working memory would be expected to have a significant effect on human information processing performance and some models of performance have specifically identified changes in working memory as causative in errors and changes in processing speed (Humphreys and Revelle, 1993). This interpretation is in direct contrast to the more traditional views of memory as 7 plus or minus 2 items (Miller, 1956) so beloved of engineers and system engineers (c.f. Chapanis, 1996). It should be noted that many design calculations assume that the 7±2 refers to data and take little or no account of the operator complexity, the number of steps (requiring place-keeping) and the generation of multiple potential results. Thus, many designs may seriously underestimate the memory load and even if chunking (Miller, 1956) of data takes place, or skilled memory usage takes place, the likelihood of forgetting or distortion of memory is very high. In addition, it has been predicted that states of fatigue will affect the capacity of the working memory and the rate at which information is processed. Thus, it would be expected that a number of factors may affect performance via their effects on working memory.

First, fatigue will decrease the capacity of working memory and increase the likelihood of forgetting. Second, fatigue will slow the rate of information processing and may exacerbate problems of capacity by slowing down the refresh rates of memory held in the temporary stores slaved to working memory. Third, any condition such as mental or physical stress and/or age which is likely to increase the rates of fatigue and the impact of fatigue will increase the limits on working memory performance. If this is compounded with increased workload because of decreased crew size this may create the conditions for performance failures.

Many of the more recent textbooks of skilled performance, such as Proctor and Dutta (1995) and reviews of human performance (such as Jones and Smith, 19992a, 1992b) acknowledge the interaction of age with factors such as fatigue and stress, with explicit recognition of the decrements relating to performance. Analyses of fatigue effects, clearly identify possible interactions between fatigue and memory performance which may be hazardous in safety critical systems (Caldwell, 1997). It is certainly true that older adults report fewer items in a delayed report tasks and the difference is more marked with increased delays in reporting, suggesting an inability to sustain information in sensory memory, prior to selection for transfer to working memory (Walsh and Thompson, 1978). There are also deficits in specific types of working memory performance and related activities, such as speed of information processing, storage of information in memory, and formation of recollections and associations (Proctor and Dutta, 1995), which degrade with age and are likely to have significant effects on performance in the highly dynamic and cognitively demanding air-warfare environment. It should be noted that each sortie requires the absorption of significant amounts of information relating to target disposition, threats and various other factors.

Integrative Human Factors

In many respects this represents a typical case where integrative human factors is required to acknowledge the range of operators using equipment, the conditions they operate under and the variation in the levels of demand. An older operator, with heavy task demands occurring after heat stress, long shifts and under time pressure represents the worst possible case. Training can help to improve memory performance (Ericsson and Delaney, 1999) but it cannot eradicate many of the basic effects attributable to fatigue, such as failure to execute actions as a result of interruption. It is known that experts tend to remember information more effectively than novices (Green and Gilhooly, 1992) but training may not counteract all the possible effects on working memory, such as stress or fatigue, which effect older individuals more. While it is possible that extended experience and training can reduce workload, by increasing automaticity, there are no such effective countermeasures to fatigue, stress or acute time pressure. Indeed, the catalogue of accident reports, failures to manage trained for events adequately and incidents or near misses, is replete with cases where these factors are possibly at work (c.f. Beatty, 1995; Brookes, 1996; Brookes, 1992; Faith, 1996; Stewart, 1992).

Many times the events or conditions contributing to accidents occurred or worsened at the change of shift, when operators were tired. Or, early in the morning when the body clock of operators is at an all-time low incidents have become serious accidents. There are likely to be significant fatigue effects which are a result of the sleep debt and circadian disruption resulting from operating out of the regular time zones. In addition, there are social effects such as seniority which comes from age and may make older operators reluctant to accept that they are making errors in such conditions. It is possible fatigue may make older individuals reluctant to seek assistance or confirmation when they are genuinely making errors. Consider the interpretation of events in Tenerife, where

two 747s collided on the runway, for many of these issues concerning age, seniority, ability to interpret rapid information exchange and the willingness to accept junior operator's input.

The Role of Working Memory

Working memory is essential for thinking, problem solving, and decision making, which is particularly critical in complex environments where multi-modal interfaces are used to manage multiple tasks with dynamically changing information. Indeed, failures in working memory or processing strategies adopted to circumvent memory limitations are frequently cited as contributors to accident and incident development in military systems, where such control systems exist (Redmill and Rajan, 1997).

If one accepts that military operations are uncertain, dynamic and unpredictable environments then the role of working memory becomes paramount in relation to decision making and planning. This is particular the case where operators are forced out of automatic operation, by novel or unexpected events, and they are required to interrogate data and ascertain the best possible course of action without obvious cues to guide performance, as more recent models of decision making would suggest (Beach, 1998; Klein, 1997; Mosier and Skitka, 1996). The older operator, struggling to keep their workload levels manageable and within their own cognitive capacity limits is ill-suited to handle unusual events. In addition, older individuals inferior ability to work flexibly may be related to the issues concerning working memory, attention, or both.

Executive Functions and Age

It is generally agreed that some of the most significant functions associated with decision making and planning rely on frontal-lobe functions (Kolb and Whishaw, 1996). These functions may be critically related to working memory capacity and the ability to inter-relate different items of information in explicit awareness.

> "After many years of neglect, the study of consciousness has forced its way back into the mainstream of experimental psychology. I have presented a case for regarding conscious awareness as one of the functions of the central executive component of working memory. I have furthermore suggested that its main advantage is that it provides a system that allows reflection and planning to replace a more direct reactive mode of operation." Baddeley (1993, p. 26).

It is worth noting that models such as that of Beach and Mitchell (1990) consider cases where individuals make straightforward decisions and simply adopt or reject a plan of action. This would present little difficulty to an individual in terms of the cognitive burden in working memory. While it is probably true that such decisions represent the most frequent case in air-warfare it is equally possible that the critical events are not as easy to manage and they are the cases in which the aircraft, the pilot or both are lost.

It is also the case that simple decisions in air warfare can be dependent on multiple sources of information that must be integrated, as will be discussed later, and this requires operations to create a single image that in turn drives effective decision making. Beach and Mitchell (1990) consider the case where each decision has multiple candidates where a single choice may be easily made or where a more protracted decision making process takes place. It should be considered that the memory burden for such iterative processing of multiple alternatives is overwhelming for an operator in a busy and hostile air warfare environment, particularly if they are flying alone i.e. in a single-seat aircraft. Each alternative must be recalled, each evaluation of each alternative and each operator applied to determine each alternatives value. It would be easy to lose track of alternatives tested, evaluations made and operators to apply. Put into the context of a stream of information from on-board sensors, off-board sensors and uncertainty the whole process would be frighteningly complex. It is easy to see why experienced operators frequently select the familiar options and inadvertently take the low and high risk choices because they fail to adequately assess the alternatives (Huey and Wickens, 1993). It is important to note that is exactly this type of information capture and information manipulation that is indicative of air warfare and other highly dynamic environments, it is also the same type of task where older individuals have more difficulty.

Working memory is usually conceived of as a mental workspace which contains activated memory representations that are available for processing (Stoltzfus, Hasher and Zacks, 1996). Although many have emphasised the structural aspects of working memory there are accounts which stress the functional significance of ancillary processes such as attention (Pashler and Johnston, 1998). Taken together the structural and functional accounts emphasise the importance of such processes in integrating new, recently acquired information with long-term information to generate appropriate responses to environmental demands

(Radvansky and Zacks, 1997). As authors have noted when attempting to make sense of a narrative relating a murder:-

> "To be successful you must mentally retrieve and integrate this information to create a mental representation of the situation in which the murder took place. Furthermore, you must be able to successfully retrieve this representation when there are later references to the crime situations you have experienced and read about." Radvansky and Zacks (1997, p. 173).

Consider that accidents, like that of the 737 at Kegworth, suggest that there can be a failure to integrate information absorbed at the start of flight and the later equipment failures observed in flight. In the Kegworth accident it is possible to speculate about the mis-reading of instruments but prior to that potential mis-reading were events suggesting different interpretations of the on-going events which the crew may not have been cognisant of at the point of impact. Thus, they did not review their fatal decision making error.

The same place keeping functions, for tracking sequences of events, must take place with regard to a specific sortie in which it may be possible to retrieve the wrong events concerning the current sequence of events. Indeed, the normalisation of experience and the casting of actual experience into schematic understanding was the basis of early work on long-term memory (Bartlett, 1932). What is likely to be gained in recall or retrieval with explicitly acquired schema is lost in corruption or distortion of events to fit with an existing prior schema. This may explain why more experienced operators are less effective at managing novel events when their performance is compared to more junior crews. Paradoxically, the greater body of knowledge available to experienced pilots may lend itself to greater difficulties in recalling the actual sequence of events without distortion. Thus, it is easy to see why more experienced pilots tend to be affected by the representative heuristic and are susceptible to the confirmation bias, as they have a potentially wider range of schema to shoe-horn the current events into. As a result it is easy to appreciate why older and more experienced operators are more likely to produce poorer responses to novel events (Huey and Wickens, 1993) because they tend to seek such processing shortcuts to avoid memory limits. Indeed, it may their experience of decreasing capacity which forces or encourages them to seek such shortcuts more frequently as time passes. Or, it may represent the tendency towards satisficing (Simon, 1955) where operators adapt their input to match perceived demand. Accurate "Situation Models" (Johnson-Laird, 1983, 1989) will undoubtedly effect decision making performance and may undermine those judgements made where information must be integrated without prejudice, derived from earlier experience.

Validity Working Memory as a Predictor of Pilot Performance

It is hardly surprising that digit-span recall tasks, which measure an aspect of working memory capacity, are significant predictors of pilot performance because of the highly dynamic environment pilots operate within. There are no attempts to measure the variations of working memory with fatigue, time of day and to consider the likely effects of fatigue on working memory performance though. It is blithely assumed that the capacity of working memory remains constant. Studies on control room staff working for the Police suggest that there are noticeable changes across the time of day and there were results indicative of differences with age (Murray, 1998) and these are supportive of the changes described in the literature (Proctor and Dutta, 1995). Anecdotal observations on 43 crews at a night Tactical Leadership Exercise certainly suggest that the same effects would be found amongst older aircrew. Older crews and supervisory staff experienced greater difficulty in retaining the information required to accomplish tasks.

Working memory may play another significant role in the development and maintenance of expert performance (Ericsson and Delaney, 1998). In addition, the use of more effective executive control of resources like working memory and attention, via meta-cognitive strategies, may be significant in achieving higher levels of performance during skilled or expert performance, without the imposition of an additional cognitive burden (Ericsson and Delaney, 1998). There are suggestions that ageing may result in poor recall of information recently processed because of changes in working memory (Stine and Wingfield, 1990). The effective reductions in memory performance with ageing has clear implications for situational awareness in the cockpit and the effectiveness of decision making.

Training and Age

The current philosophy for aircrew training favours the use of younger entrants. The syllabus for United States Air Forces trainees (Linares and Lloyd, 1996), for many different programs, is quite extensive and an early commencement is required to successfully complete the training with sufficient time to have a reasonable period of active service. There is a belief that enrolment of younger trainees will result in rapid training

because younger aircrew can more readily absorb the complexity of the new systems, particularly in fast-jet training. Starting crews at earlier ages would potentially give them a longer serving career at peak performance because they would be able to serve at younger ages for longer. However, it has been suggested that experience, through the application of schematically stored knowledge, can compensate for the effects of age (Hess, 1990). The use of prior knowledge to counteract the effects of ageing supports that view that greater training experience at an early age will help to future-proof the cognitive performance of operators against the future effects of ageing, as they approach the end of their service career.

Youthful entrants may have a number of cognitive qualities which may make them more suitable for fast-jet training, such as general processing speed, working memory capacity, the ability to acquire information, and better control of attention. There are clearly significant variations in these abilities in the general population which require that such aptitudes are selected in the recruitment phase. The contrast in these abilities and qualities is only likely to be significant when the individuals reach their late twenties and early thirties, when compared to school leavers (Schaie, 1983). If training commences in the late teens or early twenties there are likely to be fewer differences, none which are significant. Some textbooks suggest that there is a modest rise in verbal IQ across the twenties and little change in performance IQ - loosely associated with spatial ability (Belsky, 1990), so one might expect that training could commence in either the late teens and early twenties. The real issue concerns how long an individual can profitably be expected to serve before their performance deteriorates.

At the other end of the service, when aircrew are likely to be coming to the end of their career, there may be more significant effects. It could be argued that system developers should take adequate care to assess the cognitive demands of their equipment in relation to that group because they are likely make up a significant number of the serving forces as a result of the demographic shift in the population. There may be good reasons to retain experienced operators for longer in smaller serving forces to ensure the continuity of performance levels with expertise. Taken together with the time to progress from signing up to operational deployment, with the modern sophisticated weapon systems, any increase in the length of service will have a profound impact on cognitive performance in older personnel. Thus, in summarising the argument so far it has been suggested that age will play a significant part in performance directly via its effects on working memory performance or via the effects of fatigue, time of day effects and the rigidity or inappropriateness of thinking associated with biased cognition.

The trend towards smaller crew complements, at sea, on land and in the air, with the merging of roles across previously distinct branches of the services are likely to exaggerate the need for careful examination of the cognitive burden in future systems, as more is demanded of individuals. Modern fighter/strike aircraft, in swing or multi-role deployment, now require the pilot to execute air-defence and surface attack roles with the added complication of the single-seat aircraft, removing the valuable support obtained from the navigator or weapon system operator (WSO). The range of weapon systems carried are very wide and the parameters required to deliver the different types of package for optimum effect are varied, which only increases the burden on the single-seat operator. This in turn increases the likelihood of mode errors which are recognised as a common problem leading to major errors, incidents and accidents (Woods, Johannesen, Cook and Sarter, 1994)

Working Memory and Task Performance

Researchers, such as Engle (1996) have presented evidence that individual differences in the capacity of working memory predict performance in a wide variety of real-world information acquisition tasks and with respect to retrieval tasks under conditions of controlled and effortful search. The difference is not in information capacity per se but in the attentional capacity to maintain information. Taken with the earlier evidence of Pashler and Johnston (1998), this supports the emphasis on youthful selection and it clearly underlines the importance of both structural and functional aspects of the trainees inherent abilities. This would support the importance of selection based on task switching capacity and digit span performance, but open up the possibility of other factors playing an important part, such as meta-cognitive skills or executive control ability.

Interestingly, it has been found that examination of age differences in short-term memory using the digit span test indicate that there is little noticeable decline of capacity with age. If the task is subtly altered to require translation of the digits into reverse order, reverse digit span, there are deficits with age and this test is probably a more accurate reflection of flexibility of processing involving the central executive to monitor the process (Woodruff and Birren, 1983). Thus, automaticity and non-executive functions can be sustained over large periods of the life-span but the management of more complex processes which is a true measure of an effective functional working memory, cannot. This general view can easily be used to justify more careful consideration of performance evaluation and modelling with older

operators to ensure the long-term operability of new systems and equipment, particularly when the new systems include reductions in crew complement and increased reliance on individual operators. In simple terms, the more demanded of the individual operator the more care needs to be taken with the changes in operator capability with age, as the risk of failure increases. There should clearly be no simple reliance on the convenient 7±2 formula of earlier times. Indeed, one can argue that if operations of any complexity are required then the memory loading should not be greater than it needs to be because of the need for recall of the operators, applying them to process data and monitoring the results of those operations.

In conclusion, there are at least three major issues associated with changes in cognition in ageing aircrew. The first issue concerns the longevity of service. Longer periods of service may result in individuals, who are valued for their expertise, and who are too expensive to replace. However, the older individuals may be less capable of performing the highly demanding tasks required of them if designs are not evaluated with older crews in mind. The second issue, concerns the introduction of systems with reduced crew complements and increased automation with greater cognitive demands on individual operators. This makes it more expensive to train operators, increasing the need for retention, and it may result in a steeper fall in capability on the part of older operators as a consequence. The third issue is related to the merging of roles and the increased need for multi-tasking. The young minds of highly selected trainees are likely to be more capable of task-switching than the ageing aircrew but they will experience the same decline in performance with age.

Thus, the long-term prognosis for certain design choices needs careful consideration with respect to changes in cognitive function with age. Experience suggests that advances in information technology and agent-based decision support is unlikely to appear in the cockpit in time to compensate for declining cognitive performance in aircrew (Press, 1999). Thus, care must be taken to future-proof system designs against the well-documented decline in cognitive function with age.

The Bandwidth Problem

There are school textbook problems that frequently begin "It takes ten men two days to dig a trench, how many days would be required...". In air warfare this issue takes on new meaning because the question concerns the number of men and automated systems required to process information quickly enough to respond. This air warfare problem is altogether different for a number of reasons.

First, the duration of the task in the schoolbook problem can expand and contract in a manner that is impossible for operators in air-warfare. In air-warfare, the use of beyond-visual range weaponry, first look-first kill infra-red search and track (IRST), off-board sensing increases, and the move to reduced crew complements makes time of response an even more critical factor. A simple analysis of skilled behaviour indicates that increasing the number of stimulus alternatives decreases the rate of response, according to Hick-Hyman law (Proctor and Dutta, 1995) and that is what is happening in the air-warfare environment. The crews are presented with more information from many more on and off-board sensors, resulting in a greater qualitative range of behavioural cues. This in turn should slow the crews down because they have to resolve more information.

Second, the number of men involved in any task cannot increase easily because communication between operators in air-warfare has costs. In single-seat air-to-air engagements communication is a cognitive burden to the operator because they have to prepare exchanges and receive or acknowledge them. In air-to-ground or surface attack roles communication in the air is virtually impossible because of the need for stealthy ingress and egress. In tactical battlefield management of the air-to-air or air-to-ground crews the operators must co-ordinate the different strike, fighter, EW and SEAD assets to ensure that the attack is pursued successfully with the minimum number of losses on the friendly side. The effects of small changes in cognitive capability may not be observed in the capability to pursue the individual tasks but in the integration of the information into a bigger picture and the effective communication of that picture to others in the combined air operations team.

Third, the range of broadcast information from off-board sensors is about to increase as information is passed around the digital battlefield allowing different crews to have immediate access to imagery from reconnaissance UAVs and various other intelligence platforms (Thornborough, 1995; Press, 1999).

The increase in available information is happening at a point in time when the crew sizes are likely to shrink in the different platforms, with all fighter and attack aircraft moving to single-seat. There have often been comments about the capability of F-16 and F-18 single seat crews to take on the multi-role or swing-role attack capability because of the complexity of the information they need to absorb and the possibility for being overwhelmed by the torrents of information. It should be remembered that the temporal distribution of events within the single-seat cockpit could vary much more than that in a two-seat cockpit. The major point is the continuing reliance on the pilot to integrate the available information to make effective decisions and the

demands on their working memory. Any tendency for the pilot to shed tasks or to fail to process information would increase the amount of error in decision making and decrease the quality of performance outcomes. In the limiting case the pilot would become a victim but such difficulties could increase the possibility for blue-on-blue or collateral damage in abortive attacks as well.

There is a greater possibility for cognitive lockup with high rates of data throughput as the pilot struggles to maintain skill-based processing because the response to events is automatic. If unusual or unexpected events occur the pilot will find they have to quickly shed tasks in order to evaluate and then respond to the critical series of events. Even if cognitive lockup does not occur the pilot may be subject to thematic vagabonding as each event suggests a new perception of the situation. The high data rates, the poor quality of analysis, or the loss of significant information could jeopardise the quality of decisions taken as recognition primed decision making is undermined.

Thus, in a battlefield rich in information the greatest problem will be the integration of the information into good situational awareness. The adoption of crude large scale integrated visual displays, helmet mounted displays, multi-modal input/output will not improve the quality of performance because the rate limiting step is largely internal to the human operator. Even if presentation capability is improved the operators ability to capture the information declines with age as well.

It is the ability to absorb and digest information in order to synthesise a cognitive model of the world situation in order that effective decisions are taken which is the key issue. The use of automation, such as a Defensive Aids Sub-System to protect the aircraft is a good example of a technology that will not significantly improve this situation. On the one hand, a DASS can automatically dispense chaff, flares or other alternative EW decoys systems when the pilot is heavily involved in other tasks. However, the pilot may not be aware of the type of threat or the quantity if they are allowed to disengage from the defensive tasks, leaving the automation to manage itself. Thus, situational awareness is significantly impaired by a highly automated system because it encourages the development of monitoring or supervisory roles which humans are ill-suited to (Mosier and Skitka, 1996). The situation would be different if the DASS engages the pilot in a *sensible* de-briefing statement during, after or both during and after the activation of the system. Thus, the pilot would be able to improve their situation awareness by checking on the frequency of emitters and identifying the possible systems used. This could be instrumental in warning the pilot about the use of new systems with variable frequency emitters, new ranges or greater power which might undermine their own capability. Having such an on-board wild-weasel would be extremely useful. Any future demands for a zero-loss war using air-power will require effective use of electronic intelligence (ELINT) with immediate availability of access to information collected.

The major point is that any increases in sensing capability must be shadowed by effective sensor integration and additional interpretation by intelligent agents which are capable of communicating the *picture* in the way a good Weapons System Operator (WSO) or navigator normally would. A secondary point is that cognitive overload will seriously undermine the rate of learning as the capability to self-monitor and review progress or mistakes will be seriously curtailed. This in turn means extended and more expensive training regime.

Working Memory

Working Memory is a construct describing a system which involves the processing of an on-going stream of information. There are at least three different descriptions of where bottlenecks occur in the processing of information which are difficult to resolve within the available literature. One theory proposed by Wickens (1992) suggests that multiple processing resources exist which can process visuo-spatial codes or audio-linguistic codes and when tasks do not use the same resources they can occur in parallel. Another theory of processing suggests that input and output processing of information in highly practised tasks is largely accomplished in parallel and it is only complexity of the response-selection or intermediate processing that acts as a critical rate determining step (Pashler and Johnston, 1998). A third theory, developed by Baddeley and colleagues (c.f. Gathercole and Baddeley, 1993) suggests that both of the previous descriptions are correct. In place of the response selection or intermediate processing problem Baddeley has posited a central executive that is a limited resource needed to direct processing. In place of the processing resources Baddeley has proposed modality specific slave stores for information processed in working memory based around phonological and visuo-spatial storage systems.

The model accepted in the analysis of information processing during multi-task multi-modal processing, typical in air warfare, will affect the predictions derived and the strategies taken to resolve the so-called bandwidth problem. Care must be taken to ensure that the variations in memory and processing performance attributable to other factors are not forgotten in the process of adopting these different models for analysis purposes. The key issue is over what range performance would be expected to vary and what would be the limiting cases over which the total air-warfare task varies.

Working Memory in Air Warfare Situational Awareness

The best way to envisage the significance of working memory in warfare is to identify a task and then to consider the changes that might occur with crew reductions and then to consider the way in which limited working memory capacity might further impinge upon the performance associated with the different information processing tasks the operator(s) are required to accomplish. A good example, which applies to the air-to-air, air-to-ground, multi- and swing-role aircraft is the construction of a mental model of the on-going air picture.

The first input that both air-to-air and air-to-ground crews have access to is the Radar Warning Receiver, which in its simplest form can give the directions of the emitter and the frequency of the emitter. From the emitter frequency it may be possible to deduce the type of radar emitter and from that it logically follows the type of aircraft, surface to air system or surface ship which carries the system and the possible degree of threat. This is the purpose of electronic intelligence to allow operators to quickly establish the nature of the threat. It is equally possible to find that emissions are carefully controlled in duration or other aspects of their characteristics to confuse or spoof the operators ability to interpret the signal. Occasionally a receiver may incorrectly indicate the nature of the source and friendly and enemy forces are mis-classified. Thus, the Radar Warning Receiver is only one source of information from which crews can get information and it may not always be accurate. Thus, an additional task is monitoring the effectiveness of the system in use. A major limitation of the RWR is it provides bearing only, and both the range and the altitude of the enemy aircraft are unknown. To obtain those other sensors and information must be used.

Another type of information may come from advanced infra-red search and track system, like those pioneered by the Russian designers, to enable silent or emission controlled attacks to be pursued under the guidance of ground controller intercepts at long-range, with the closing end-game using on-board sensing. Another on-board sensor generally available to fighter and fighter /attack aircraft is the radar system which depending on its type and the signal processing capability may be able to find and track multiple targets. The problem with on-board radar is the emission of electro-magnetic signature which informs enemy aircraft of the presence and the type of the aircraft, which undermines the first-look first-kill stealthy capability. Radar is currently a necessarily evil which may be required to activate the seeker head at long-range to ensure a good lock in difficult conditions e.g. look-down position where ground returns must be separated from the target. If the operator prefers to remain stealthy then the only other alternative to on-board radar is surface or air based radar from surveillance aircraft such as the E3-D, AWACS aircraft operated by NATO and French forces, the E2-C Hawkeye operated by French and U.S. Navies, or the AEW Sea King variant. Airborne radar will provide relative bearings of aircraft around a Bull's Eye position but a major limitation is the accuracy of the altitude of enemy aircraft. Altitude can really only be given accurately by more local radar with data-links and that means switching on the on-board sensing. The major benefit of the off-board sensing capability is the capability to limit emissions to the times when it is actually required for driving weapons systems before the weapon's own seeker captures the target.

The major point of this discussion is the requirement to fuse information from diverse sources to ensure that the image created is validated by independent sources. Thus, the target's bearing, range, altitude, speed, radar cross section, its historic profile in combination with its known capability in terms of weapons and range, help predict its future course. In recent conflicts the ability of the coalition forces and the allied groups to effectively suppress airborne and surface based enemy air defence has meant that the opposition have been unable to mount an effective Defensive Counter Air (DCA) force. Thus, the requirement for accurate air picture may be underestimated because coalition forces were sorting small numbers of enemy aircraft and Surface to Air Missile (SAM) systems. This balance can quickly shift with evolving surface missile system capability and air-to-air missile capability. Thus, there is little room for complacency.

As one can imagine the construction of the air picture is quite a difficult task in and of itself. Thus, it forms quite a formidable task alongside that of flying the aircraft in difficult or hostile conditions. For example, large numbers of highly effective SAMs present a considerable threat which must be managed with on-board Electronic Counter Measures (ECM), decoys, jammer aircraft or chaff. Electronic Warfare (EW) assets or Suppresion of Enemy Air Defence (SEAD) are a limited resource, whether they are carried within a package as under-wing stores or on other aircraft as specialist units. Recent events have shown that such assets in the form of specialist aircraft like the EA6B Prowler represent a very valuable and scarce resource. The significance of this is the ultimate requirement of aircraft to defend themselves from air and surface threats with on-board systems than must be managed carefully and used wisely. In simple terms, this is another on-going task that requires a degree of intelligence to effectively use the assets and to prevent their depletion to the point where the aircraft is vulnerable to attack. These management of these systems normally

present a cognitive burden to the pilot or crew of the aircraft.

Thus, the management of Defensive Sub-Systems and Construction of the Air Picture represent highly demanding cognitive tasks which are mission critical, safety critical and more importantly time critical in that they require sure and certain responses to imperative cues. In air warfare, as in so many other aspects of warfare, speed is essential. This would indicate that defensive and intelligence gathering aspects of the air warfare environment require that information is accessible at speed from working memory. The delays or failure to recover information which can occur with retrieval from long-term memory are simply unacceptable with such information. Given the temporal imperative it might be expected that any continuous monitoring or performance task such as flying are expected to interfere with intelligence or defensive tasks. Thus, the shift from a two-seat cockpit to a single-seat cockpit could be extremely problematic if the pilot is unable to shed tasks such as flying, defensive sub-system management or intelligence gathering. The decline in specialist assets within all air-forces around the world means that individual crews now have to assume many more roles other than air-to-air or air-to-ground attack of previous fleets.

Thus, strategies are required to avoid the perils of cognitive overload possible in a single seat cockpit. For example, the integration of information from disparate sources using sensor fusion may help the pilot to make effective decisions about the threat levels from different enemy assets or the use of a intelligent agent to manage defensive aids may reduce the demands of that aspect of air warfare. However, it is clear that effective air-warfare performance would normally reflect the interaction of intelligence gathering with the management of defensive sub-systems. In some situations it may be better not to reveal one's position or intent by dispensing a decoys or chaff. The automation of the sub-systems, and both the management and monitoring of the tasks by the human in the loop require careful consideration. If the pilot is out-of-step with the intent, capability, responses or effects of the systems for sensor fusion or defence then serious consequences may ensue.

The key message that can be taken from this discussion is that air-warfare involves highly demanding tasks that impose significant memory burdens and require the integration of information, actions and consequences. If the sub-systems introduced to manage the cognitive burden address only partial tasks and fail to support the linkages between data gathering and skilled behaviour then performance can never be as effective as it would be in two-seat configuration. Many forces opting for the convenience of single-seat aircraft suggestively point to the success of aircraft like the F-15C and the F-16. However, mess rooms are replete with anecdotal stories of two seat crews in less effective aircraft defeating superior aircraft or *leakers* wreaking havoc on large packages as they overwhelm the SA of Combat Air Patrols (CAPs) with cognitive overload. It is worthwhile recalling that with single missile kills an aircraft like the Su-33 carries ten lethal weapons, the Su-35 twelve missiles, the MiG-29 six missiles and the MiG-31 up to eight. Thus, one aircraft can inflict significant losses on a single large package.

Stores Awareness

While it is possible that crews can check their weapons, it is better for them to aware of how many missiles they and their wingman have available and what type, so that decisions can be taken quickly about the decision to press on, in the face of strong opposition. A major point in favour of western forces has up until now been the capability of the weapon systems in particular the air-to-air missiles and particularly the AMRAAM whose capability as a force multiplier is undeniable. Recognising this only serves to underline the precarious nature of the balance of power.

Fallacy of Faster Throughput

The eighties was a period in which it was proposed that advanced interfaces would be developed. It was proposed that when these interfaces were adopted they would increase the capability of operators to process greater rates of information with naturalistic, sensor fused and intuitive interface technologies. This was the era of helmet technology that never was (except in Russia), the sensor integration / fusion that relied heavily on the human operator, the broad band interface that adopted speech to manage tasks like communication that had been mis-managed in previous aircraft, and which proposed virtual reality technology as a substitute for reality when there were well established problems with other forms of synthetic imagery.

The reason why the *pump more information in* philosophy could never work was the complete ignorance of certain key features apparent in the basic models of working memory. First, models of working memory proposed that a central executive would manage processing when tasks were difficult and unpredictable and it is a limited processing resource. Clearly low predictability and uncertainty describe the nature of air-warfare. Second, the central executive is a limited resource that has a finite switching time and this limits the number of sustainable of streams of conscious processing from different modalities or tasks. Thus, greater dis-integrated information would simply create a greater error rate with increased task switching,

incomplete processing and failed retrieval or misinterpretation as a consequence. Third, the central executive is required to sustain information in working memory so it is not simply the case that processing is delayed but that information is actually lost from consciousness. External access from displays is impossible because the signals change over time.

Consider again the combined RWR and radar image, from off or on-board sensing. It should be possible to intelligently manage this information in a complicated environment to predict the general location of threats in future epochs by tracking their movement. Thus, it would be possible to restrict the scanning of an active array radar and reduce the possibility of detection. At the same time it would be adequate enough to track potential threats and respond if the enemy radar locks on. This kind of predictive and restrictive use of radar might be accomplished by an intelligent agent. This is unlikely because of the degree of signal processing and computation required to visualise the information. It is task integration of this type which might allow the pilot to confidently share tasks with on-board automation but it is not likely in the next generation of aircraft.

Postscript

After presenting this paper it became clear that a number of related issues should have been addressed.

First, the issue of demands on working memory imposed by the design of systems can have effects throughout the period of service of the system operator which can in turn result in cascade effects from one period into another, with both costs and performance implications. A very complicated system can increase the initial training requirement and cost, as well as the risk related aircraft and pilot losses. The delays imposed by any protracted training can in turn shorten the effective operational or combat-ready phase of the operator's service, increasing the cost of delivering that performance per unit time. There are also no guarantees that the effects of poor design may not persist into the operational phase of operation and create further losses under high workload or special conditions. For example, the problems experienced with the computer controlled ascent and descent systems and moding in the Airbus seem to good examples of problem persistence into operational service (Woods, Johannessen, Cook, and Sarter, 1994). Failures to address working memory constraints might equally prove to be hazardous and some of the omission and commission errors in aircraft operation may be attributable to working memory failures or errors. At the end of the pilot's service any unreasonable demands from the interface upon the pilot's working memory may result in poorer performance, continued fatalities or the need for reductions in the period of active service. It is important to stress that failures in working memory would only be expected in the most demanding of conditions when the multi-task multi-modal aspects of the operators role becomes mission, safety and time critical. Given the dramatic changes about to occur in the nature of the aircraft available and their capabilities, the crew reductions proposed for future aircraft and their relationship to current practice it is difficult to predict the future outcomes. However, it is noticeable that strike aircraft like the F-15E Strike Eagle and the strike version of the Rafale will have two seats. It is also worth noting that the single seat versions of the SEAD F-16 have not been as successful as the Wild Weasel and EF-111 Raven packages in the Gulf War, although that may reflect changes in experience and knowledge of the opposition. Consistent with the view that crew size has a significant effect consider the vital role of the EA-6 Prowler aircraft in providing both soft and hard kill capability with regard to Suppression of Enemy Air Defence (SEAD) with its four man crew.

Second, the population of pilots or operators tested in studies is not homogeneous throughout the analysis periods used for examining performance with respect to ageing. This is explained by the commonly used phrase – "There are old pilots, there are bold pilots but no old, bold pilots". In simple terms, the process of de-selection or physical attrition through fatalities in accidents will remove those pilots who push too close to the edge of the envelope. It should be noted that no moral judgement is made in this respect because there are many military analysts that have strongly supported the need for such individuals in times of war (Vandergriff, 1999). Thus, attrition through accidents will remove those pilots of excellent quality in challenging manoeuvres and the poorer pilots who make simple un-forced errors.

Third, a major part of the argument proposed with respect to working memory is the combined effects of prolonged stress, fatigue, flying out of time zone, and flying at night. All of these factors in themselves can have small detrimental effects on performance but together, experienced chronically, they will have greater effects on ageing pilot as a result of their reduced ability to quickly recover. With smaller numbers in the potential pilot pool, careful consideration must be made concerning the benefits of age in terms of wisdom and the effects on likely performance.

Lastly, there are practical considerations concerning the retention of ageing crews because they may have experience which can provide useful insights for the more junior members of staff. However, care must be taken to retain only selected highly experienced staff with valuable experience, such as actual operational deployment or specialist skills, and this must be tempered

with knowledge concerning any changes in material operated by potential foes and changes in their doctrine. It is clear that training and operational matters are still affected by persistence of views drawn from cold-war experience and training. The modern battlefield has changed dramatically and the future generation of combat ready pilots must respond to that ill-defined challenge.

A Postscript on Working Memory in Skilled Performance

Finally, a recent paper by Ericsson and Delaney (1999) re-examined the issues concerning skilled use of memory in expert performers and it identified a number of significant issues with respect to such performance that have implications for the use of working memory in the relevant task domains. No matter what definition of working memory is accepted, and there are a number of alternatives, they all place stress on the place keeping and temporary storage of information using the mechanism of working memory. In the highly dynamic and context sensitive environment of air-warfare this function is vital to executing decision making in an appropriate manner based on conclusions drawn from current and previous information. Second, evidence reviewed by Ericsson and Delaney (1999) suggests that concurrent tasks with similar information processing requirements may not interfere but they fail to review the effects of semantic interference in concurrent tasks.

In air-warfare, given the levels of uncertainty, the use of spoofing and deception, and the consequences of failures, the crews may have to maintain several alternative hypotheses concerning the current trend of events which places a significant burden on memory. Ericsson and Delaney (1999) stress the need for extended practice in developing working memory skills in retrieving relevant information in skilled performance and largely associate that with extended practice of the skills. If the future systems have fewer operators, and more numerous and more complicated functional requirements for the remaining operators, it is clear that a conflict exists between the need to master all functions, to reach an acceptable level of skill in each, to develop skill in scheduling the different functions and to reduce the costs of training. This underlines the need for careful cognitive analysis of the functional requirements of training and the development of suitable strategies for enhancing the learning process to aid the development of skilled memory. There is clearly a very real danger of creating systems which genuinely take a lifetime to master but this a luxury that cannot be afforded when operational demands on combat ready crews are increasing. Combat roles could mean that the crew's life is terminated in advance of the final stages of skill development.

In conclusion, the ageing operator and their retention within the services present many problems and afford some advantages. There are issues touching upon the design of equipment, the selection of new recruits, the development of training, the maintenance of skill, the manning levels required, and other human factors issues, relating to the limits of human working memory. The potential information demands of future warfare cannot be dismissed and assumptions concerning the technological management and analysis of data have been so frequently challenged by failure that they need special consideration. Identifying working memory as a potential bottleneck can and should be a liberating discovery. The capability of the human processor in pattern recognition and in self-limiting of error, via insight, cannot be achieved by machine intelligence. Thus, all elements of the warfare system must accommodate the human decision maker and their memory performance to minimise the potentially fatal and catastrophic consequences of error.

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